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Full Length Article

Absorption, Bioaccumulation and Transportation of Selenium in Three Vegetables Differing in Selenium Transport Distances

Mei Yang[1,2#], Wanyi Zhao[1#], Weihong Xu[1*], Zhangmi He[1] and Deyu Feng[1]
[1]*College of Resource and Environment, Southwest University, Chongqing, 400716, China*
[2]*Crop Research Institute, Sichuan Academy of Agriculture Science, Sichuan Chengdu 610066, China*
[*]For correspondence: xuwei_hong@163.com
[#]Authors Yang and Zhao should be as co-first authors

Abstract

A pot experiment was conducted to compare the differences of growth, absorption, transportation and accumulation of selenium (Se) in three vegetables differing in Se transport distances, including cucumber (*Cucumis Sativus* L.), tomato (*Solanum lycopersicum* L.) and radish (*Raphanus Sativus* L.) exposed to soil Se levels (0, 1.0, 5.0, 10.0 and 15.0 mg·kg^{-1}). Results showed that soil application of Se (<10 mg·kg^{-1}) remarkably promoted the growth of all three vegetables by increasing plant dry weights by 5.46% to 58.2% compared to the control without Se treatment. Se concentration and accumulation in roots, stems and leaves increased with the increase of soil Se level and reached the highest when applied at 15 mg·kg^{-1}. At the same Se level (≤15 mg·kg^{-1}), Se concentration in roots, stems and leaves of radish was higher than tomato and cucumber. Se enrichment and its translocation factors for radish were also significantly higher than tomato and cucumber. Compared to tomato and cucumber, radish is more suitable for selenium-rich vegetable cultivation under soil applied Se≤15 mg·kg^{-1}.

Keywords: Exogenous Se; Se absorption; Vegetables; Bioaccumulation factor (BCF); Transportation factor (TF)

Introduction

Selenium (Se) is one of the essential trace elements for living organisms (Schiavon and Pilon-Smits, 2017), known as 'the protective agent of life' (Zhao *et al.*, 2017). Studies have shown that if the Se intake of human body is less than 50 μg·d^{-1} for a long time, it may result in series of health problems, such as fertility decline, Keshan disease and Kaschin Beck disease (Mora *et al.*, 2015). With the continuous understanding and improvement of the physiological function of Se, its nutrition and supplementation have attracted more attention. For the Se supplement in human and animal, the inorganic Se not only has the problem of low absorption and conversion rate, but also causes the adverse effects on human and animal health because of the narrow range of safe doses of Se (Bañuelos *et al.*, 2017). Many studies have shown that biogenic Se is the most safe and efficient method of Se supplement in human body (Longchamp *et al.*, 2015; Nagy *et al.*, 2015; Liao *et al.*, 2016). Plants can transform the absorbed exogenous inorganic Se into the safer and more effective Se containing metabolite, such as *SeCy*, *SeMET* and *MeSeCy* (Guignardi and Schiiavon, 2017). Therefore, Se application in crops can improve nutrition level of human and animals in low-Se or Se-deficiency areas.

Vegetables as the essential food for people's daily diet play a very important and irreplaceable nutritional role in maintaining normal physiological function and improving health. Therefore, it has important practical significance and broad prospects to carry out the applied research and promotion of Se-rich vegetables. Among the general crops, the strongest ability of Se accumulation belongs to cruciferae, such as mustard greens, radish, broccoli and turnip (EI-Mehdawi *et al.*, 2015; Thiruvengadam and Chung, 2015; Mahn, 2017; Puccinelli *et al.*, 2017). At present, there are few reports on the differences in the absorption, transportation and enrichment of Se in long, medium and short distances. This experiment with cucumber (*Cucumis Sativus* L.), tomato (*Solanum lycopersicum* L.) and radish (*Raphanus Sativus* L.) as the experimental crops studied the effects of different Se treatments on the growth, its absorption, transportation and accumulation in these vegetables.

Materials and Methods

Plant Material and Experimental Treatments

The seeds of cucumber (*Cucumis Sativus* L.), tomato (*Solanum lycopersicum* L.) and radish (*Raphanus Sativus* L.) were bought from Xiema Farmers Market in Beibei District,

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Chongqing, China. The experimental soils were the purple soils from the Purple Soil Base at Southwest University. The soil was collected from depth within 0-20 cm by multipoint sampling method, naturally dried, and then ground through 5 mm sieve. The soil pH was 7.11 with the organic matter of 16.80 $g \cdot kg^{-1}$, total nitrogen 1.40 $g \cdot kg^{-1}$, available nitrogen 101.63 $mg \cdot kg^{-1}$, available phosphorus of 46.09 $mg \cdot kg^{-1}$, available potassium of 171.92 $mg \cdot kg^{-1}$, cation exchange capacity of 30.3cmol·kg^{-1}, total Se of 0.38 $mg \cdot kg^{-1}$ and available Se of 0.020 $mg \cdot kg^{-1}$.

The pot experiment was conducted at glass greenhouse of College of Resources and Environment of Southwest University from March 4, 2016 to July 12, 2016. Five Se levels (0, 1.0, 5.0, 10.0 and 15.0 $mg \cdot kg^{-1}$) prepared from Na_2SeO_3 were set up. Before transplanting, Se fertilizer mixed in soil and balanced for 2 weeks. Two plants per pot of cucumber, tomato and radish were planted in plastic containers (25 cm in diameter and 17 cm high), each basin was loaded with 5 kg of air-dried soil screened with 5 mm sieve. The total dosage of nitrogen, phosphate and potassium fertilizers were 180 $mg \cdot kg^{-1}$, 150 $mg \cdot kg^{-1}$ and 150 $mg \cdot kg^{-1}$ as NH_4NO_3, KH_2PO_4 and K_2SO_4, respectively. The experiment was performed in triplicate, in a randomized complete block arrangement. During the cultivation, deionized water was used to maintain soil water content at 60-80% of the maximum water holding capacity of the field. Cucumber was harvested after 100 days, tomato after 125 days and radish after 60 days, respectively.

Analysis of Se Concentrations in Soil and Plants

Soil and plant samples were ground and digested at 170°C using 10 mL of acid mixture (8 mL of ultrapure nitric acid and 2 mL of perchloric acid) (Kyodan *et al*., 1988). The acid mixture was heated until white smoke appeared; added with 10 mL of 6 $mol \cdot L^{-1}$ hydrochloric acid, and the mixture was heated until the white smoke re-appeared (Kyodan *et al.*, 1988). The residual sample was then diluted in 25 mL of ultrapure water (Kyodan *et al.*, 1988). The concentration of Se in the solution was analyzed using hydride generation atomic fluorescence spectrometry (PF6.3, Beijing Purkinje General Instrument Co. Ltd., China). Bioaccumulation factor (BCF) referred to the ratio of Se concentration of roots, stems and leaves in vegetables to soil applied Se, and transportation factor (TF) was the ratio of Se concentration over shoots to roots (Li *et al*., 2015).

Statistical Analysis

The statistical analysis was performed using SPSS21.0 statistical software. The effects of interaction among Se levels on dry weight of plant, Se concentration and accumulation for various vegetable species were subjected to a two-way analysis of variance (ANOVA; *i.e*., species and Se treatments) followed by the least significant difference test ($P < 0.05$).

Results

Effects on Plant Growth

With the increase of soil Se level, plant dry weights of the three vegetables increased first and then decreased. At 5 $mg \cdot kg^{-1}$ Se level applied to soil, plant dry weights of each vegetable reached the maximum and increased by 19.2%, 10.0% and 20.8% respectively compared to the control. Minimum plant dry weights of all vegetables was found for 15 $mg \cdot kg^{-1}$ soil applied Se, which decreased by 14.51%, 18.52% and 28.34% respectively compared to the control (Table 1).

The root and shoot ratio of radish was significantly greater than tomatoes and cucumbers at each and similar Se rates. With the increase of soil applied Se, root and shoot ratio of radish and tomato decreased first and then increased, while the root and shoot ratio of cucumber increased along with the rising soil Se level. At 15 $mg \cdot kg^{-1}$ soil Se, the root and shoot ratio of cucumber reached the maximum value, which was 1.24 times higher than of the control, while the root and shoot ratio of radish reached the minimum value, of 0.73 times for control. At the soil 5 $mg \cdot kg^{-1}$ Se level, the root and shoot ratio of tomato reached the minimum value of 0.72 times as high as of the control (Table 1).

Se concentration in Plant Parts

Se concentrations in roots, stems, fruits and leaves of the three vegetables increased with the increase of soil Se level. Se concentration of radish was in order of root > leaf > stem, and of tomato and cucumber were in order of root > leaf > stem > fruit (Fig. 1). The maximum values of Se concentrations in roots, stems, fruits and leaves of the three vegetables was found at 15 $mg \cdot kg^{-1}$ soil Se level. At this level, Se concentrations in leaf and stem were in order of radish > tomato > cucumber, where leaf Se concentration in radish was 1.36 and 1.69 times higher than in tomato and cucumber, respectively. Se concentration in fruit was in order of tomato > cucumber, whereas Se concentration in fruit of tomato was 1.26 times higher than of cucumber. Se concentration in root followed the order as radish > cucumber > tomato, whereas Se concentration in root of radish was 1.62 and 1.51 times higher than tomato and cucumber, respectively. This Se concentration in roots of cucumber was 1.07 times higher than of tomato.

Se accumulation

With the increase of soil applied Se level, Se accumulation in roots, stems, fruit and leaves of the three vegetables increased (Table 2). The highest of plant Se accumulation was found in tomato at 15 $mg \cdot kg^{-1}$ Se, followed by cucumber. At same Se treatment (from 0 to 15 $mg \cdot kg^{-1}$), Se accumulation in tomato was in order of leaf > stem > root ≈ fruit.

Table 1: Effects of different selenium levels on dry weight of three vegetables

Se levels/ mg·kg^{-1}	Dry weight/g·pot^{-1}												Root/Shoot		
	Root			Stem			Leaf			Fruit					
	Radish	Tomato	Cucumber	Radish	Tomato	Cucumber	Radish	Tomato	Cucumber	Radish	Tomato	Cucumber	Radish	Tomato	Cucumber
0	5.11± 0.03b	2.79± 0.75a	1.87± 0.12c	0.85± 0.10b	25.67± 0.47a	17.25± 0.06c	1.45± 0.05c	14.21± 0.07b	11.59± 0.72a	-	19.28± 0.61ab	20.26± 0.94a	2.22± 0.01c	0.04± 0.06ab	0.04± 0.03b
1	5.12± 0.57b	2.80± 0.28a	2.21± 0.27ac	0.85± 0.04c	25.79± 1.89b	23.54± 0.74a	1.57± 0.01b	16.36± 0.17ab	12.06± 0.41b	-	20.17± 0.31b	21.19± 0.32ab	2.11±0 .01a	0.05± 0.04a	0.04± 0.04a
5	6.21± 0.51ab	2.25± 0.22c	2.29± 0.27ab	0.96± 0.04b	30.29± 0.41b	21.56± 1.01a	1.66± 0.01c	16.51± 0.98a	13.56± 0.01a	-	19.07± 0.16a	24.14± 1.77a	2.37± 0.03c	0.03± 0.01b	0.04± 0.04bc
10	4.11± 0.61c	2.88± 0.10ab	2.11± 0.14a	0.64± 0.0b	21.39± 1.89c	17.98± 0.24a	1.61± 0.02a	15.38± 0.15b	13.10± 0.77c	-	21.44± 0.74b	19.31± 0.10a	1.82± 0.02a	0.05± 0.01b	0.04± 0.06bc
15	3.79± 0.09c	2.19± 0.37b	1.95± 0.79a	0.43± 0.07a	19.67± 0.79b	14.58± 0.77c	1.59± 0.03c	12.73± 0.43b	9.51± 0.17a	-	18.37± 0.19a	17.11± 1.94ab	1.62± 0.03b	0.04± 0.03a	0.05± 0.08a

Different letters (a, b, c) indicate significant difference at $P \leq 0.05$ among different species at the same Se level

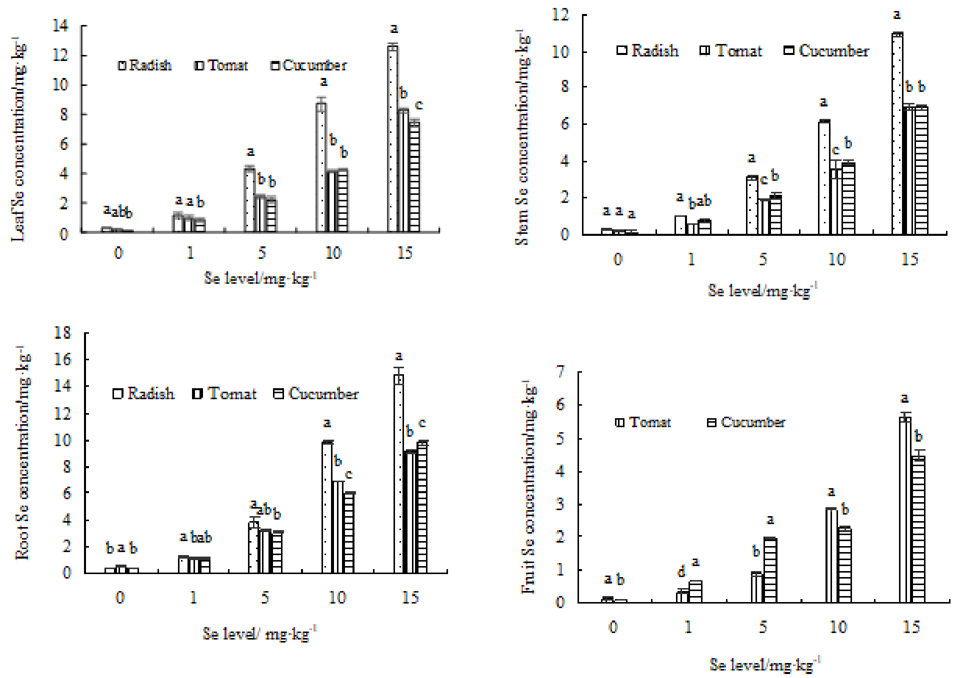

Fig. 1: Effects of different selenium levels on selenium concentration of roots, stems, leaves and fruits in three vegetables
Different letters (a, b, c) indicate significant difference at $P \leq 0.05$ among different species at the same Se level

When soil Se level was from 0 to 5 mg·kg^{-1}, Se accumulation of cucumber was in order of fruit > leaf > stem > root, while at soil Se level between 10 and 15 mg·kg^{-1}, Se accumulation of cucumber was in order of leaf > fruit > stem > root. At the same Se treatment (from 0 to 15 mg·kg^{-1}), Se accumulation of radish was in order of root > leaf > stem.

Se Bioaccumulation and Transportation

The bioaccumulation (BCF) and transportation factors (TF) of Se in radish were significantly higher than tomato and cucumber (Table 3). With the increase of soil Se, the $BCF_{leaves/soil}$ of Se in radish decreased first and reached to the lowest point at 10 mg·kg^{-1} Se, and then increased; while in tomato, it reached the lowest at 1 mg·kg^{-1} and highest at 10 mg·kg^{-1} Se, which was respectively 0.61 times and 2.16 times higher than control. With the increase of soil Se level, the $BCF_{leaves/soil}$ of Se in cucumber increased first, then decreased and reached the highest at 10 mg·kg^{-1} Se. The $BCF_{root/soil}$ of Se in radish significantly declined compared to the control at 1-10 mg·kg^{-1} Se, and then increased at 15 mg·kg^{-1} Se. The $BCF_{root/soil}$ of Se in tomato reached the maximum at 10 mg·kg^{-1} Se and was 1.73 times higher than the control, while the $BCF_{root/soil}$ of Se in cucumber reached the maximum at the level of 5 mg·kg^{-1} Se with 2.04 times higher than control.

The transportation factor (TF) of Se in tomato increased at ≤5 mg·kg^{-1} and declined when ≥5 mg·kg^{-1}, and reached the lowest at 15 mg·kg^{-1} Se, which further reduced by 40.9% compared with the control. With the increase of soil Se level, the TF of Se in radish and cucumber increased first

Table 2: Selenium accumulation in root, stem, leaf and fruit of three vegetables

Se level/mg·kg-1	Se accumulation/μg·pot-1											
	Root			Stem			Leave			Fruit		
	Radish	Tomato	Cucumber	Radish	Tomato	Cucumber	Radish	Tomato	Cucumber	Radish	Tomato	Cucumber
0	2.03±0.13a	1.36±0.13b	0.63±0.13c	0.15±0.10c	3.02±0.42b	1.55±0.09a	0.58±0.01a	5.94±0.39b	2.86±0.09c	-	2.45±0.10b	8.95±0.37a
1	6.31±0.06c	3.19±0.55b	2.45±0.02a	0.57±0.01a	7.60±0.78b	3.41±0.71c	1.41±0.02b	10.60±1.97a	10.67±0.19a	-	2.22±0.12a	11.54±0.03b
5	23.55±0.46a	7.23±0.98b	6.98±0.71bc	2.03±0.15c	20.56±0.77ab	19.90±0.95a	5.27±0.07a	34.24±1.97b	24.31±0.73c	-	7.89±0.88b	28.31±0.46a
10	24.01±0.09c	19.98±0.84b	12.71±0.03a	1.91±0.54a	25.17±0.32b	21.72±1.32c	8.04±0.28c	38.72±0.03b	44.78±0.77a	-	21.80±0.97a	23.69±2.78ab
15	29.06±0.24a	20.11±0.66b	19.15±0.03bc	1.79±0.51c	49.82±0.28b	16.35±0.99a	10.30±0.39a	57.78±1.64b	41.57±0.92c	-	24.30±0.25b	17.40±1.98a

Different letters (a, b, c) indicate significant difference at $P \leq 0.05$ among different species at the same Se level

Table 3: Comparison of BCF and TF of selenium in three vegetables

Se level / mg·kg-1	$BCF_{root/soil}$			$BCF_{stem/soil}$			$BCF_{leave/soil}$			TF		
	Radish	Tomato	Cucumber	Radish	Tomato	Cucumber	Radish	Tomato	Cucumber	Radish	Tomato	Cucumber
0	1.23±0.22a	0.64±0.07b	0.60±0.31b	0.68±0.02c	0.14±0.87ab	0.12±0.12a	0.89±0.54a	0.41±0.57b	0.34±0.07c	0.55±0.004c	0.28±0.005b	0.12±0.005a
1	0.76±0.14c	0.69±0.02ab	0.66±0.02a	0.42±0.55a	0.11±0.39b	0.08±0.95c	0.64±0.87c	0.25±0.83ab	0.29±0.96a	0.70±0.005a	0.31±0.007b	0.22±0.009bc
5	0.59±0.08a	0.61±0.12ab	1.23±0.22c	0.30±0.64c	0.17±0.28b	0.66±0.02a	0.49±0.21a	0.30±0.14b	0.89±0.54c	0.74±0.005c	0.28±0.005ab	0.23±0.008a
10	0.58±0.18c	1.11±0.03b	0.76±0.14a	0.278±0.51a	0.15±0.73b	0.42±0.55c	0.43±0.32c	0.89±0.11b	0.63±0.87a	0.75±0.008a	0.21±0.005b	0.17±0.004bc
15	1.11±0.65a	0.61±0.54b	0.59±0.08c	0.295±0.78c	0.19±0.05b	0.30±0.64a	0.65±0.93a	0.35±0.74b	0.49±0.21c	0.67±0.002c	0.17±0.004ab	0.13±0.004a

Different letters (a, b, c) indicate significant difference at $P \leq 0.05$ among different species at the same Se level

and then decreased. The highest TF of Se in radish was 1.37 times higher than the control at 10 mg·kg-1 Se, while the highest TF of Se in cucumber was 1.85 times higher than the control at 5 mg·kg-1 Se. The TF of Se in the three vegetables was in order of radish > tomato > cucumber.

Discussion

Application of Se fertilizer could help in its absorption in crops and improving levels in animals and human bodies (Ros *et al.*, 2016). It is an effective way to supplement Se in low-Se areas to increase its crop concentration by soil application (Oancea *et al.*, 2014). Although Se is a not necessary element for plant growth, a moderate of its amount can promote growth, increase crop yield and Se concentration as evident from present study results (Nawaz *et al.*, 2014; Fan *et al.*, 2015; Temesgen *et al.*, 2015). This might be due to a moderate Se concentration in plant to improve antioxidant enzymes activity to enhance the protective enzyme system in plants. The low Se concentration can be used to improve plant productivity and promote dry matter accumulation in plants by improving and regulating photosynthesis (Pandey and Gupta, 2015; Jiang *et al.*, 2017). Golob *et al.* (2016) reported that too much Se inhibited the growth of plants. In the present study, growth of tomato and cucumber was inhibited at high Se (15 mg·kg-1), as reported by Han *et al.* (2013, 2015), Issam *et al.* (2015), Jiang *et al.* (2015). This may be due to the reason that the Se replaced the sulfur in SH- and affect the normal protein metabolism, thus inhibiting its endogenous antioxidant system, increasing the degree of intimal lipid peroxidation in cells, causing toxicity to plants, reducing photosynthetic productivity and inhibiting crop growth (Jiang *et al.*, 2015; Tian *et al.*, 2016). It was also found in present study that applying Se in soils promotes the radish growth, and even at high Se 15 mg·kg-1, the biomass (dry weight) of radish was still improved compared to control, probably because radish belongs to cruciferous vegetables which had strong characteristics of Se enrichment and its tolerance (Simon *et al.*, 2015; Schiavon *et al.*, 2016).

The absorption of Se by plants varies with species. In the present study, Se concentration in the edible part and the transportation factor of radish was the highest, probably because radish belonged to cruciferous vegetables having strong ability of Se accumulation and transportation. The highest transportation factor (TF) among three vegetables was of radish, followed by tomato, and then of cucumber. This indicates that the Se absorbed by radish roots could be more transferred to the shoots; on the contrary, cucumber roots more likely accumulate more Se. This seems that the transport of Se was related to the distance and the longer the distance, the worse the transfer efficiency, as the Se translocation in plants require the loading by xylem and phloem, parts of Se could be fixed in this process and resulting in decreased availability of Se (Li *et al.*, 2015). Selenium loaded in xylem can be transported directly to phloem through "code" and then transported to fruit (Li *et al.*, 2015) during long distance transportation, therefore, the loss of Se can also happen at code during long distance translocation, and the physiological mechanism about this aspect still needs further research. The BCF of the three vegetables reached the maximum at soil applied 1 mg·kg-1, with the increase of Se level, the BCF decreased, which was probably because high Se level in soil was more easily immobilized by iron and manganese oxides, thus reducing the bioavailability of Se (Wiesner-Reinhold *et al.*, 2017). It was also probably because the high Se level had poisoned the root system of vegetables and inhibited its absorptive capacity due to high selenite produced salt stress on vegetable roots, thus breaking the equilibrium state of osmotic pressure and making the root system unable to absorb nutrient elements (Hawrylak-Nowak *et al.*, 2013). In the present study, the distribution coefficient of Se in radish roots was always more than 70% under Se treatments because the radish belonged to root crops and produce high proportion of root biomass so its accumulation in roots was large. As an edible part of radish, the accumulation of Se in roots proved that radish was of great value in the practice of developing Se rich vegetables. However, the distribution coefficient of Se in tomato fruit was less than 20%, indicating that its low Se accumulation ability (Mozafariyan *et al.*, 2016). With the increase of Se level, its distribution coefficient for cucumber fruit declined, which was less than 20% at 15 $mg \cdot kg^{-1}$ of Se level. However, in the case of suitable Se level, its distribution for cucumber fruit was about 40% which basically met the standard of rich Se vegetables (Chi *et al.*, 2017).

The present study also revealed the effects of different Se levels on the abilities of absorption, transportation and distribution of radish, tomato and cucumber with different Se transport distances, would provide a certain theoretical basis for the development of the measures for the cultivation of Se rich vegetables. Some studies have shown that Se mainly exists in the leaves and reproductive organs of plants (Bañuelos *et al.*, 2015), which means as the leaves senescence, the Se in the leaves will be transferred and redistributed to the reproductive organs. In this study, the distribution coefficients of Se in the three vegetables exceeded 20%, among which, tomato had even up to 50%. If the Se in leaves can be transported to fruit, it is of great significance to increase Se concentration in edible part of vegetables, which needs further research.

Conclusion

Among the three vegetables, the highest Se concentration was found in the roots, followed by the leaves at 15 $mg \cdot kg^{-1}$ Se. At soil applied Se $\leq$ 15 $mg \cdot kg^{-1}$, Se concentrations in roots, stems and leaves of radish were higher than tomato and cucumber. Se enrichment and translocation factors of radish were also significantly higher than tomato and cucumber. Radish transported Se in short distance is more suitable for selenium-rich vegetable cultivation.

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